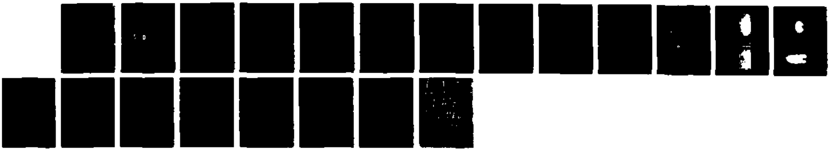
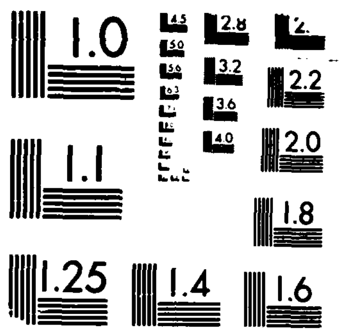
AD-A193 751   J-INTEGRAL MEASUREMENT USING MOIRE INTERFEROMETRY(U)   1/1
WASHINGTON UNIV SEATTLE DEPT OF MECHANICAL ENGINEERING
M S DADKHAH ET AL. APR 88 UWA/DME/TR-88/59
UNCLASSIFIED   N00014-85-K-0187   F/G 20/6   NL





MICROCOPY RESOLUTION TEST CHART

...REAU ... STANDARDS 1963-A

Office of the Chief of Naval Research

Contract N00014-85-0187

Technical Report No. UWA/DME/TR-88/59

J-INTEGRAL MEASUREMENT USING MOIRÉ INTERFEROMETRY

M. S. Dadkhah, A. S. Kobayashi, F. X. Wang and D. L. Graesser

April 1988

The research reported in this technical report was made possible through support extended to the Department of Mechanical Engineering, University of Washington, by the Office of Naval Research under Contract N00014-85-K-0187. Reproduction in whole or in part is permitted for any purpose of the United States Government.

Department of Mechanical Engineering

College of Engineering

University of Washington

J-INTEGRAL MEASUREMENT USING MOIRÉ INTERFEROMETRY

* M. S. Dadkhah, ** A. S. Kobayashi, *** F. X. Wang and **** D. L. Graesser

ABSTRACT

An improved moiré interferometry, which records both the vertical and horizontal displacements simultaneously, was used to determine the J-integral within the confine of a constitutive relation. J-values, which are associated with stable crack growth in biaxially loaded 2024-T3 aluminum, single edge notched specimens, were found to be path independent and increased with crack extension.

KEY WORDS

J-integral, Biaxial Loading Machine, Moiré Interferometry, Elastic-plastic Fracture Mechanics, Simultaneous displacement fields, Automated Data Reduction Displacement Fields, J-resistance curve and Stable crack growth.

INTRODUCTION

In two previous papers [1,2], one of the author and his colleagues presented a procedure for estimating the J-integral values using only the displacements vertical to the

* M. S. Dadkhah (SEM Member) is a Predoctoral Research Associate, Department of Mechanical Engineering

** A. S. Kobayashi (SEM Fellow) is a Professor, Department of Mechanical Engineering

*** F. X. Wang is a Visiting Scientist, Department of Aeronautics & Astronautics, FU-10, University of Washington, Seattle, WA 98195.

**** D. L. Graesser is a Research Engineer at the Boeing Aerospace Company, Kent, WA.

A-1

crack in a single edge notched specimen. This restriction was imposed by the requirement for rapid recordings of a transient displacement field, which was obtained by moiré interferometry, associated with stable crack growth and rapid tearing of a ductile material. Extensive error analysis showed that this estimation procedure provided reasonably accurate J-values in single edge notched specimens.

The above restriction has been removed in an improved moiré interferometry setup where both the vertical and horizontal displacements are recorded simultaneously in a single frame [3]. The improved procedure is conducive to high speed photography and a procedure was developed for determining the J-integral value exactly within the confine of the constitutive relation. This procedure was used to determine the J-values associated with stable crack growth in biaxially loaded, 2024-T3 aluminum, single edge notched specimens, 0.8 mm thick, as shown in Figure 1. Biaxiality ratios of B = 0.0, 2.0 were applied through a special biaxial testing machine [4] and stable crack growth in excess of 5 mm were obtained prior to rapid tearing. The J-values were evaluated along the three contours encompassing the crack.

EXPERIMENTAL PROCEDURE

An improved four-beam moiré interferometry system was used to measure two orthogonal in-plane displacement fields simultaneously [3]. This experimental setup is nearly identical to that described by Post [5], except that a polarizing beam-splitter and a prism are placed between the emerging moiré patterns and the camera lens, as shown in Figure 2. The beam-splitter separates the u and v displacement fringe patterns and the prism projects them onto the same frame of a photographic system.

Automated Data Reduction Displacement Fields

The data reduction scheme used in this study is an automated data reduction version of the recorded u and v displacement fields [6,7,8]. The technique was automated through the use of modern digitizing and computer equipment. The two primary pieces of equipment required are an AST Turboscan Digitizer and a Macintosh II computer. The digitized moiré patterns, which are created using the AST Turboscan system, are stored in a bit map file, which in essence contains pixel information for every point on the image. The original 38.1x38.1 mm^2 (1.5x1.5 in^2) grating area is represented by 7,200,000 pixel points in the digitized image. The program STRAIN computes displacement derivatives in either the horizontal or vertical directions. Normal strain, ε_x, is determined from the u-displacement image, i.e. $\varepsilon_x = du/dx$, while ε_y is determined from the v-displacement image, i.e. $\varepsilon_y = dv/dy$. The shear strain ε_{xy} is found by taking the derivatives du/dy and dv/dx and summing them in the fashion: $\varepsilon_{xy} = 1/2(du/dy + dv/dx)$.

The evaluation of the J-Integral is essentially a numerical integration along a loop encompassing the crack where the three strain components must be evaluated at identical points along the chosen path. Program STRAIN calculates strains at fringe center locations, which may or may not be exactly on the chosen path. Thus an interpolation program (INTRP), which calculates the strains at every pixel point along the contour in the computer image, was developed. The positions of the u and v displacement fields may not be identical in the two photographs, therefore, INTRP requires that offset values be entered relating the relative position of the "origins" in the two fields, i.e., du/dx and du/dy are calculated for the given path, while dv/dx and dv/dy are calculated for a path on the v displacement field which corresponds to the path taken on the u displacement field. This process ensures that the numeric integration is using three components of strain from the same location.

J Integral Evaluation

The evaluation of the J-Integral requires the strain components, the stress components and the strain energy density [9,10]. The three components of stress are calculated using J_2-deformation theory of plasticity for multi-axial states with a power hardening stress-strain relation. A Newton-Raphson routine was used to solve the three coupled nonlinear constitutive equations. The strain energy density is calculated using the stress and strain components calculated above.

The J-measurement, which was derived for rectangular contours surrounding the crack tip, is divided into line itegrals along the vertical and horizontal segments shown in Figure 1. The integral value of J along the vertical segments is:

$$J_V = \int_{V_1} \left[W - \left(\sigma_{xx}\frac{\partial u}{\partial x} + \tau_{xy}\frac{\partial v}{\partial x} \right) \right] dy - \int_{V_2} \left[W - \left(\sigma_{xx}\frac{\partial u}{\partial x} + \tau_{xy}\frac{\partial v}{\partial x} \right) \right] dy \tag{1}$$

and along the horizontal segments the value of J is:

$$J_H = - \int_{H_1} \left(\sigma_{yy}\frac{\partial v}{\partial x} + \tau_{xy}\frac{\partial u}{\partial x} \right) dx + \int_{H_2} \left(\sigma_{yy}\frac{\partial v}{\partial x} + \tau_{xy}\frac{\partial u}{\partial x} \right) dx \tag{2}$$

$$J = J_V + J_H \tag{3}$$

Accuracy of this J-evaluation procedure was assessed by evaluating equations (1) and (2) along a 4.2 cm contour, which did not enclosed the crack tip, using the moiré fringe data of

specimen MD031687-838. The resultant J = 49.01 (pa-m), which theoretically should vanish, was 0.4 % of the minimum recorded J-value in this paper.

RESULTS

Figure 3 shows typical moiré fringe patterns corresponding to the u and v displacement fields in a biaxially loaded aluminum specimen. Figure 4 shows the two normal strains, ε_x and ε_y, for the displacement fields shown in Figure 3. Due to large plastic deformation axial strain regions are no longer of the familiar butterfly shape. Figure 5 shows the stress-strain relation of the 2024-T3 aluminum specimen with the coefficients for the power hardening relation.

Figures 6 and 7 show the J_R-curves for uniaxially ($B = 0$) and biaxially loaded ($B = 2$) 2024-T3 aluminum specimens. Despite the maximum differences of 4.4 cm in the lengths of integration paths, the J-values for each crack length differed at the most of 8 percent. The extrapolated J_R-curves infer critical J_{Ic} = 5500 and 6300 Pa-m for uniaxially and biaxially loaded specimens, respectively.

Figures 8 and 9 show the log-log plots of the v-displacement fields toward the last crack extension increment. For a HRR field [10] to hold, the slope of these curves should be $\frac{1}{n+1} = 0.1$. The extent of the HRR fields can be estimated in Figures 8 and 9 by bounding the slopes of the v displacements to ± 10 % of its theoretical value. The extent of HRR field in this experiment was about 8.8 mm ahead of crack tip.

CONCLUSIONS

1) J is path independent for crack extensions of 4 mm for B = 0 and B = 2.

2) J_R curves are identical within the scatter of data for both B = 0 and B = 2.

3) HRR field extended 8.8 mm from the crack tip.

ACKNOWLEDGEMENT

The work reported here was completed under ONR Contract N00014-85-K-0187. The authors wish to acknowledge the support and encouragement of Dr. Yapa Rajapakse, ONR, during the course of this investigation.

REFERENCES

1] Kang, B. S.-J., Kobayashi, A. S. and Post, D., "Stable Crack Growth in Aluminum Tensile Specimens," *Experimental Mechanics*, Vol 27, No.3 (Sept 1987), pp. 234-245.

2] Kang, B. S.-J., Kobayashi, A. S.,"J-resistance Curves in Aluminum SEN Specimens Using Moiré Interferometry," *Experimental Mechanics*, (to be published 1988).

3] Dadkhah, M. S., Wang, F. X. and Kobayashi, A. S.,"Simultaneous on Line Measurement of Orthogonal Displacement Fields by Moiré Interferometry," *Experimental Techniques*. (to be published 1988).

4] Hawong, J. S., Kobayashi, A. S., Dadkhah, M. S., Kang, B. S.-J. and Ramulu, M., "Dynamic Crack Curving and Branching Under Biaxial Loading," *Experimental Mechanics,* Vol. 27, No.2, (June 1987), pp. 146-153.

5] Post, D.,"Moiré Interferometry," Chap 7, *Handbook on Experimental Mechanics*, ed. A S. Kobayashi, Prentice-Hall, Englewood Cliffs, NJ (1987).

6] Dally, J. W. and Riley, W. F.,"Moiré Methods," Chap 12, *Experimental Stress Analysis*, New York, McGraw-Hill, 1978.

7] Gray, T.G.F., McKelvie, J., McKenzie, F. and Walker, C.A., "Interferometric Measurement of J for Arbitrary Geometry and Loading," *International Journal of Fracture*, Vol. 24, (1984), R109-R114.

8] McKenzie, P. M., McKelvie, J. and Walker, C. A., "Evaluation of The J-Integral Using a High-Sensitivity Moiré Technique," *Proceedings of the 1986 SEM Spring Conference on Experimental Mechanics*, pp. 773-780.

9] Rice, J. R., "A Path Independent Integral and Approximate Analysis of Strain Concentration by Notches and cracks," *Journal of Applied Mechanics, Transaction of the ASME*, 35, 1968, pp. 379-386.

10] Hutchinson, J. W., "Singular Behavior at the End of Tensile Crack in a Hardening Material," *Journal of Mechanics and Physics of Solids*, Vol. 16, pp. 13-31, (1968).

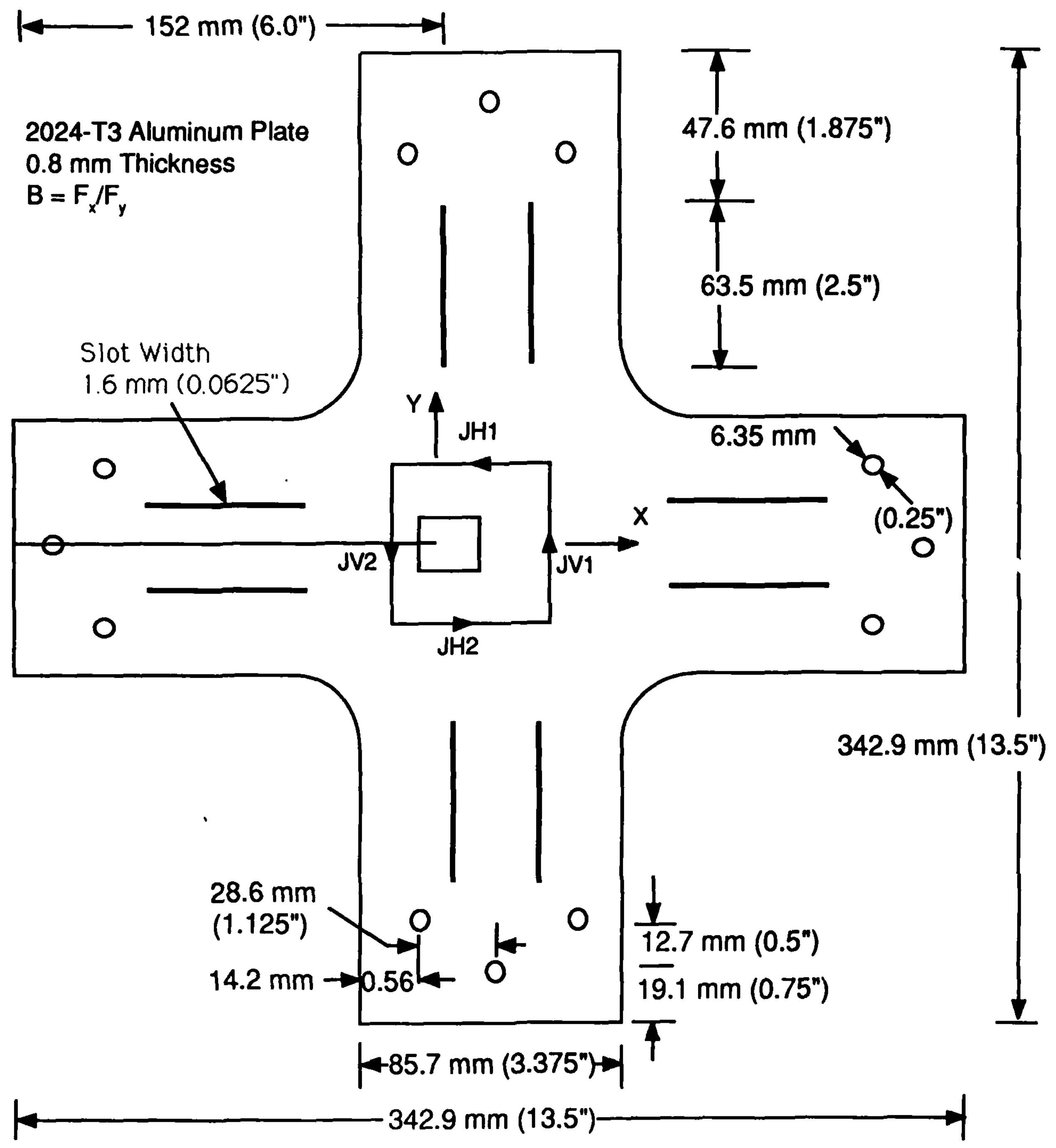


Figure 1 Specimen Configuration and J-integration Paths

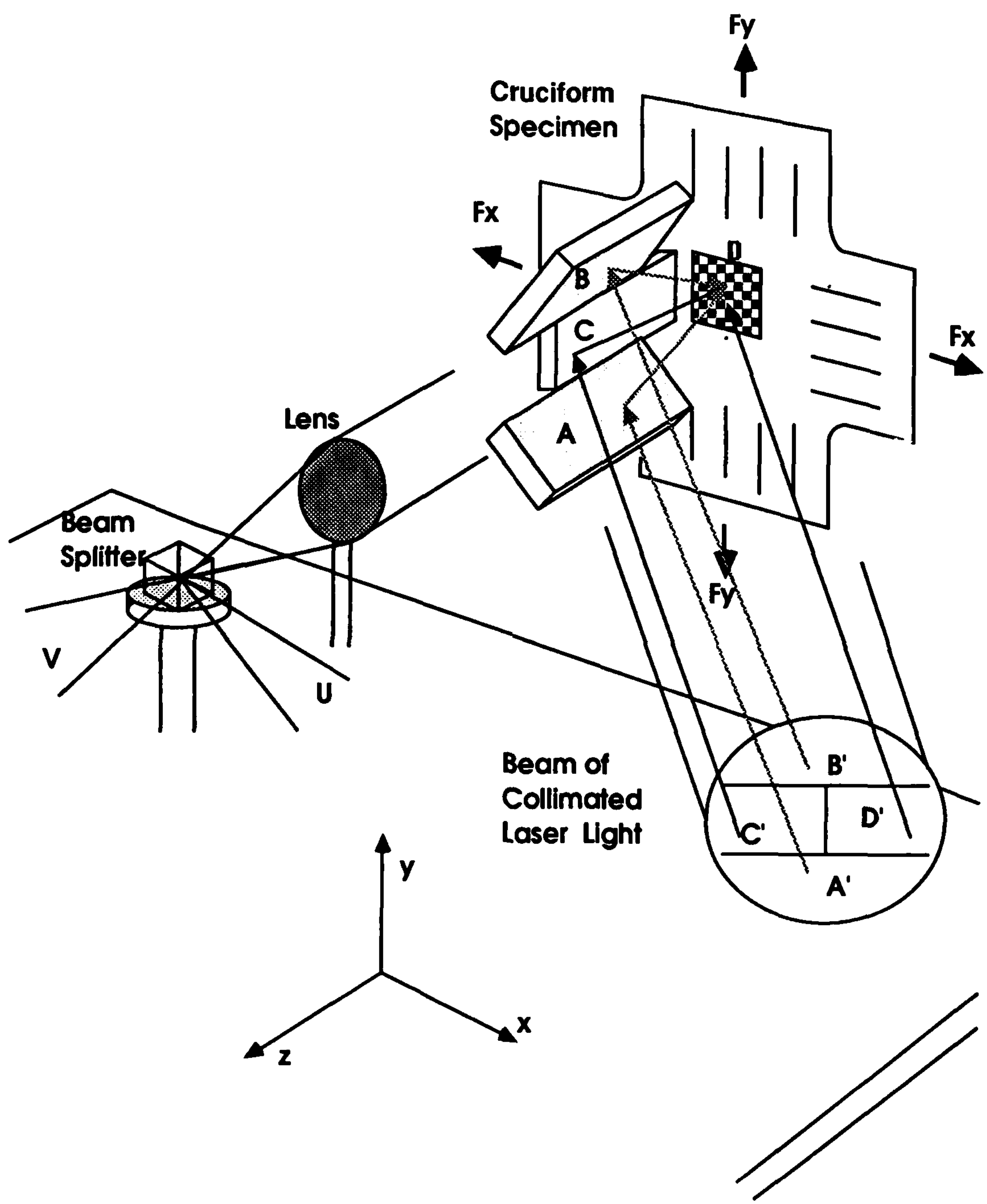


Figure 2 A 4-beam Optical Arrangement to Produce the u Pattern with Beams C' and D', The v Pattern with Beams A' and B'.

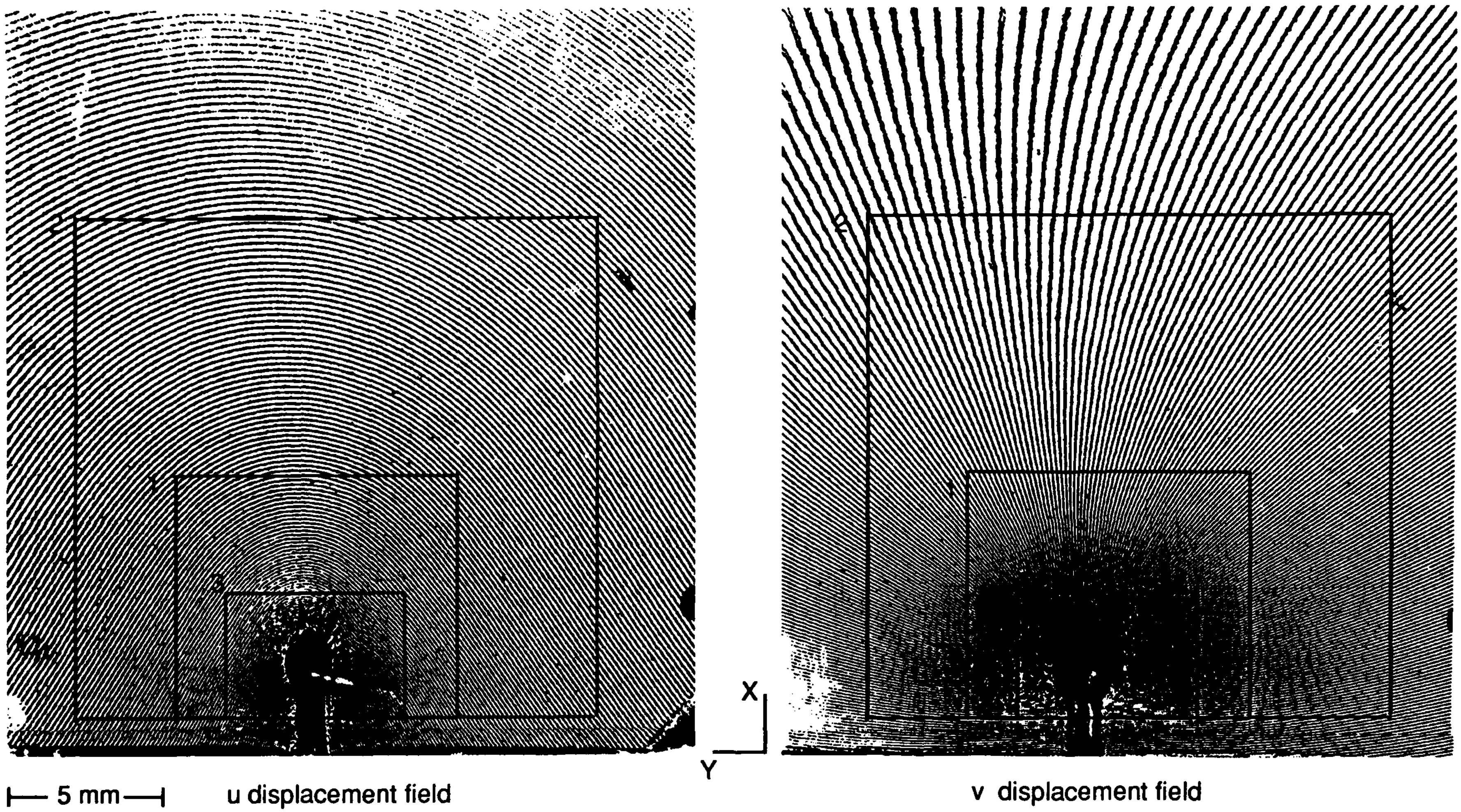


Figure 3 u- and v-displacement Fields for Test MD101987-8.
(J-integration Paths Shown in Each Figure)
F_x=17 KN, F_y=8.8 KN, B≈2.

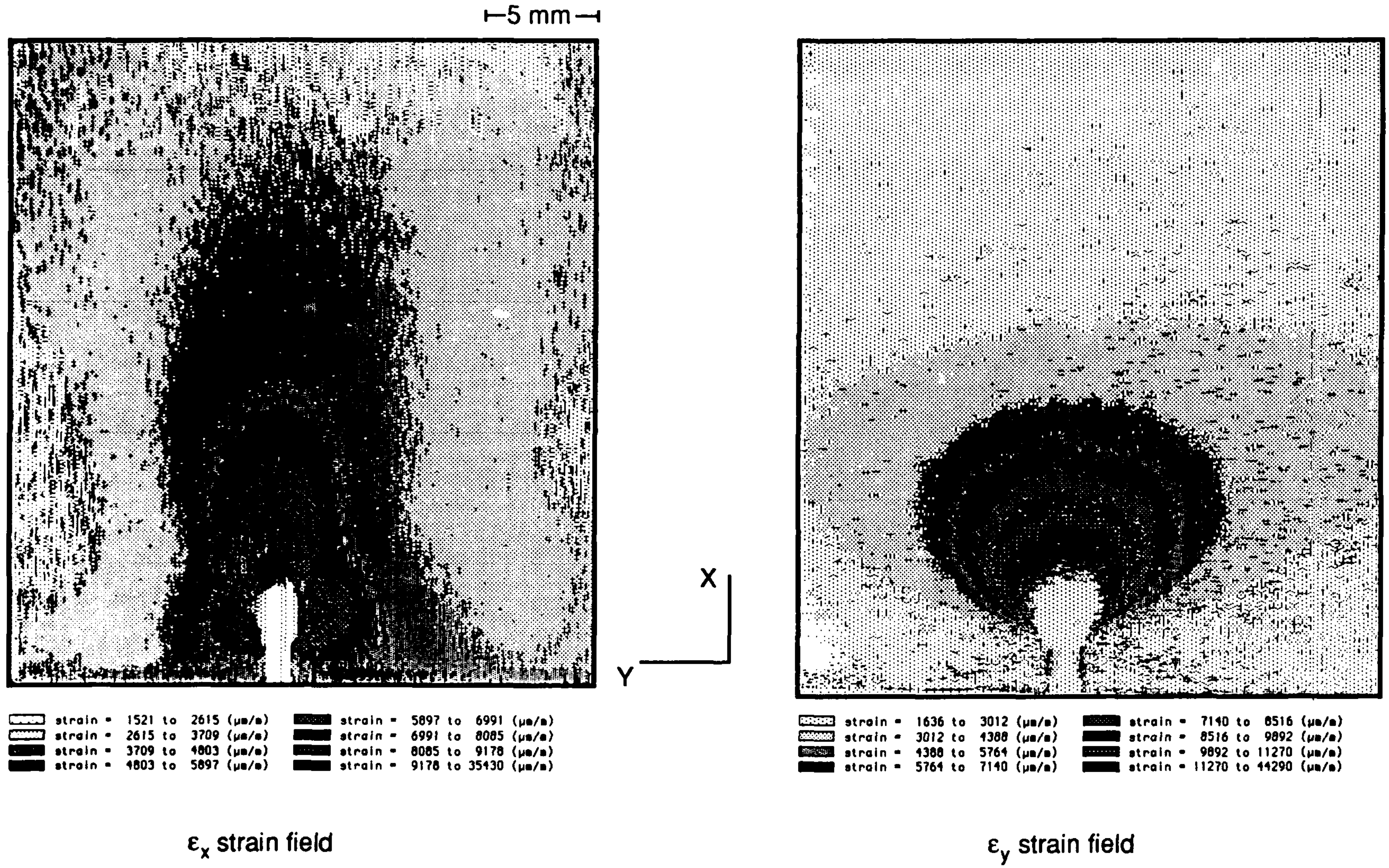


Figure 4 Normal Strain Fields in Biaxially Loaded 2024-T3 Aluminum Specimen. F_x=17 KN, F_y=8.8 KN and B≈2 for test MD101987-8.

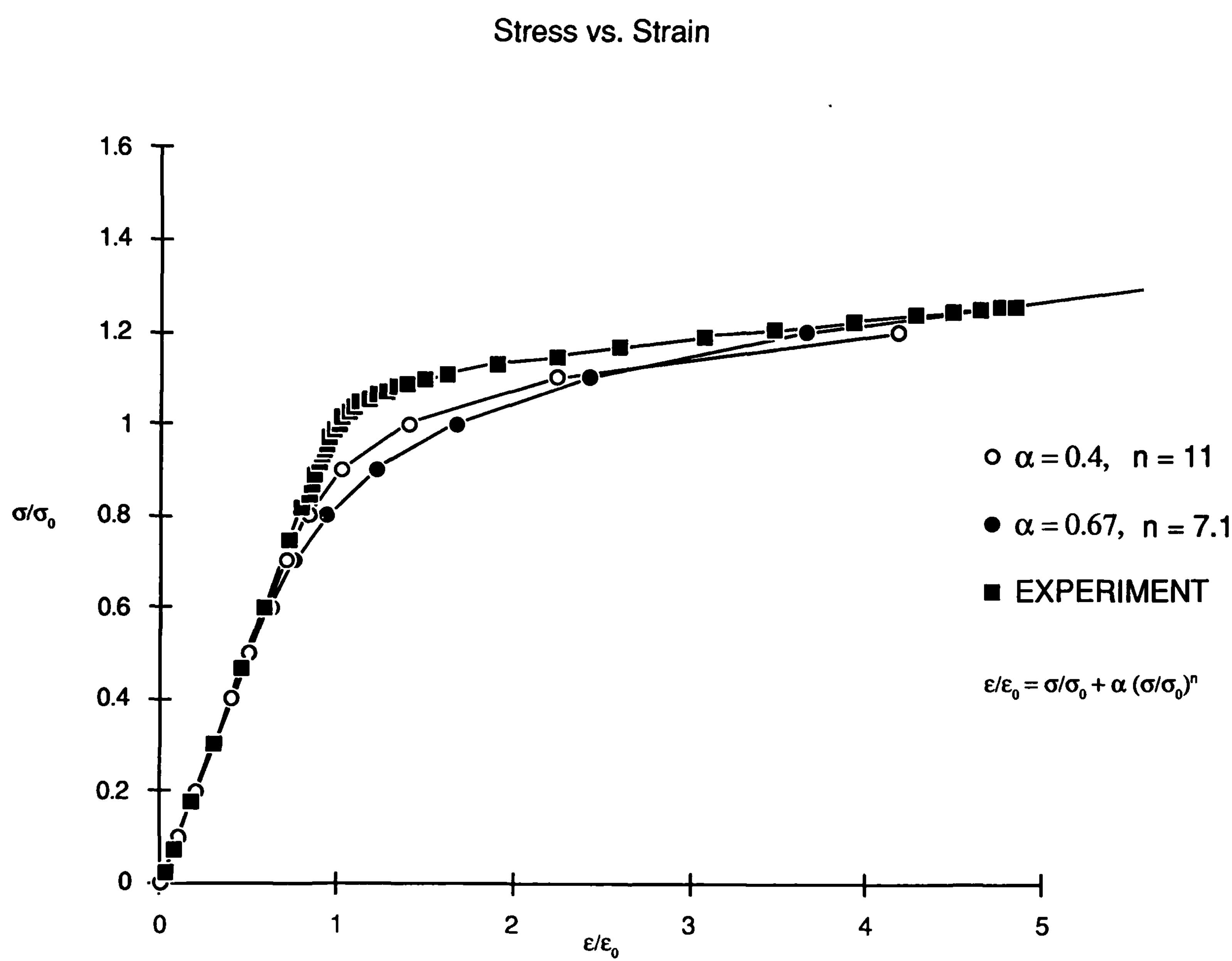


Figure 5 Stress-Strain Relation of 2024-T3 Aluminum 0.8 mm Thickness.

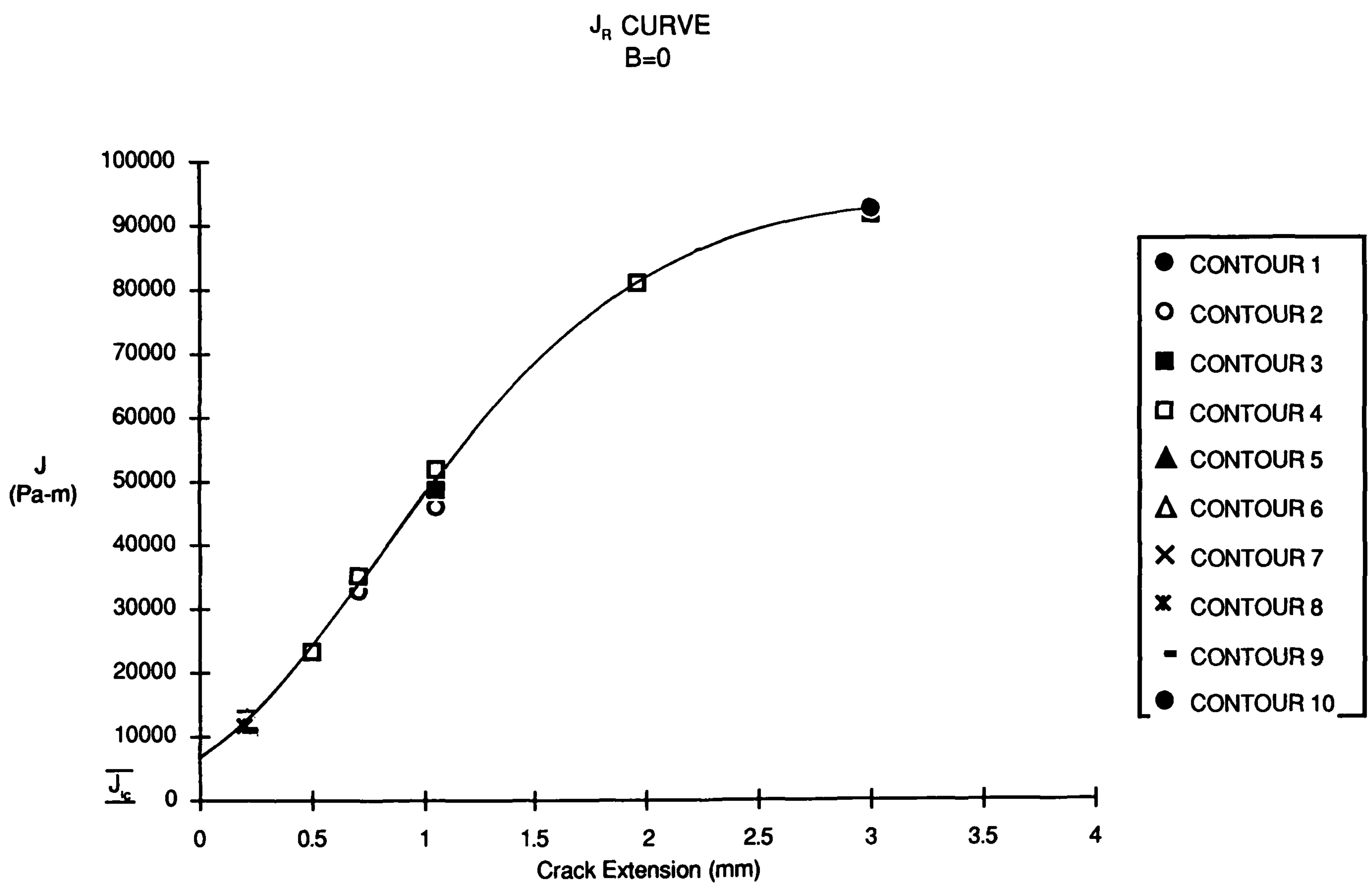


Figure 6 J Values Versus Crack Extension, 2024-T3 Aluminum Specimen MD031687, B=0.

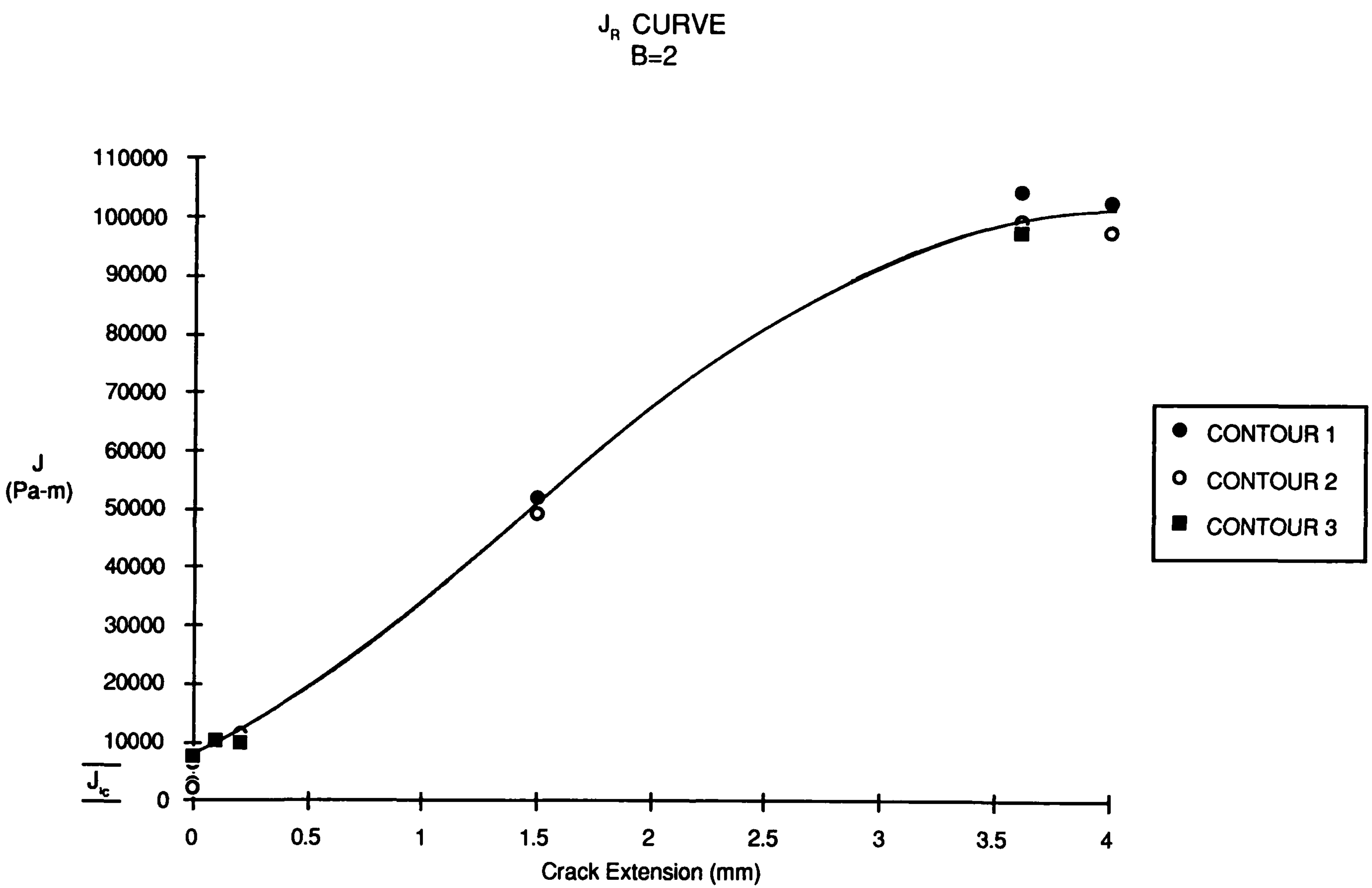


Figure 7 J Values Versus Crack Extension, 2024-T3 Aluminum Specimen MD101987, B=2.

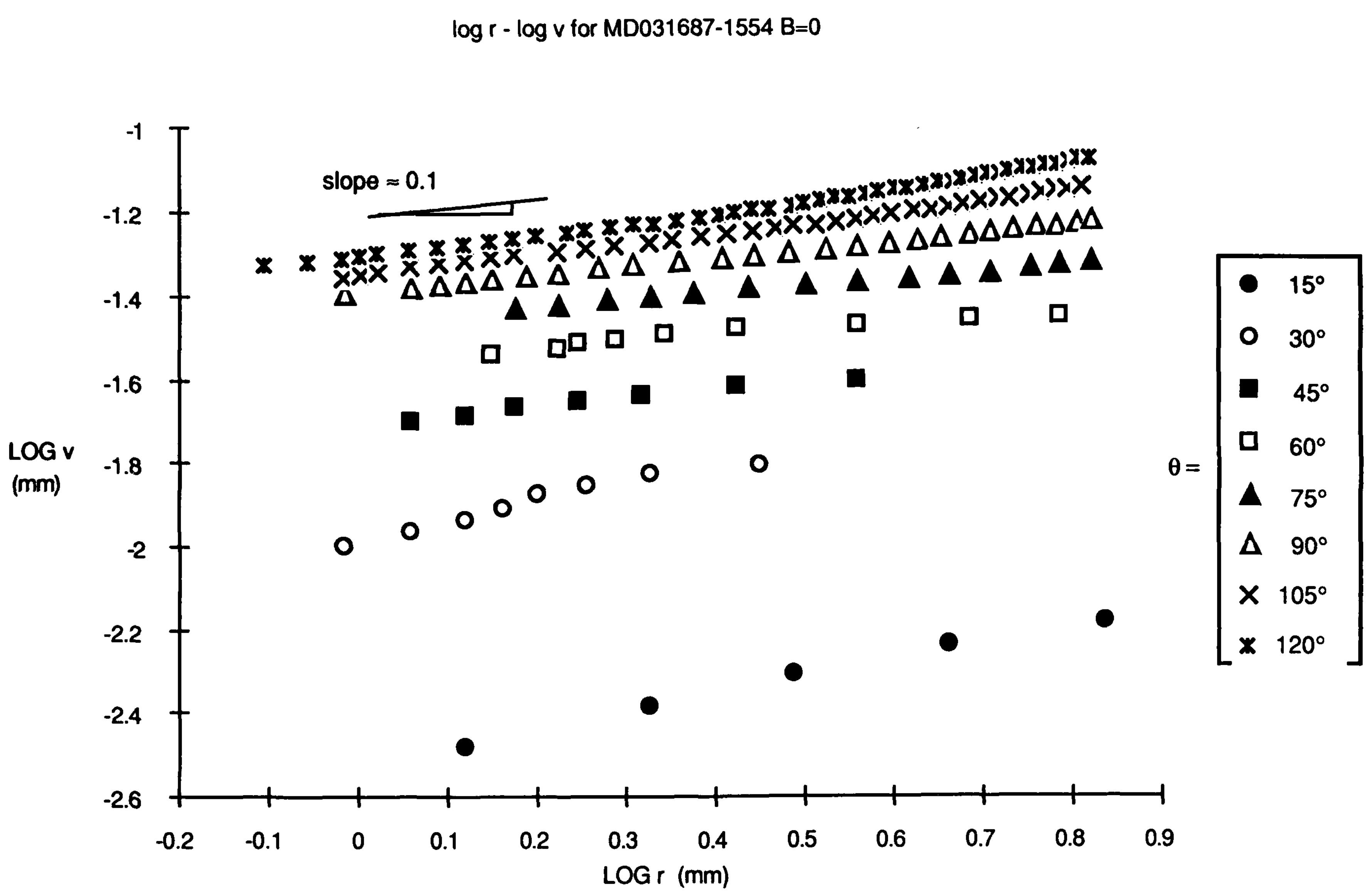


Figure 8 Log v Versus Log r Plots of 2024-T3 Aluminum SEN Specimen MD031687-1554, B=0.

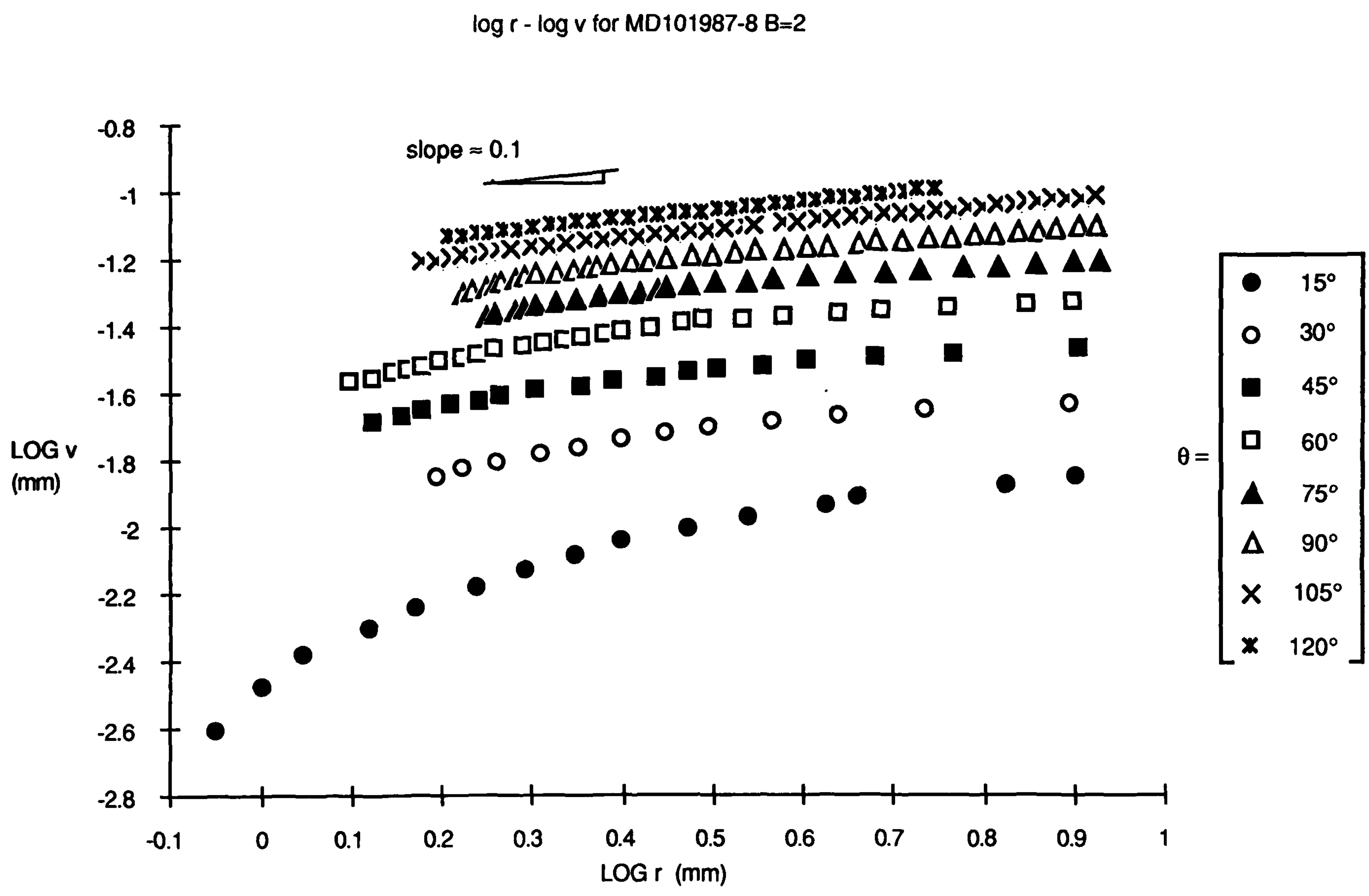


Figure 9 Log v Versus Log r Plots of 2024-T3 Aluminum SEN Specimen MD101987-8, B=2.

ONR MASTER MAILING LIST
UPDATED 7/86

Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217-5000
Attn: Code 1132SM (4 copies)

Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217-5000
Attn: Code 1131

Defense Documentation Center (4 copies)
Cameron Station
Alexandria, VA 22314

Naval Research Laboratory
Washington, DC 20375
Attn: Code 6000

Naval Research Laboratory
Washington, DC 20375
Attn: Code 6300

Naval Research Laboratory
Washington, DC 20375
Attn: Code 6380

Naval Research Laboratory
Washington, DC 20375
Attn: Code 5830

Naval Research Laboratory
Washington, DC 20375
Attn: Code 6390

Naval Research Laboratory
Washington, DC 20375
Attn: Code 2620

David W. Taylor Naval Ship
Research & Development Center
Annapolis, MD 21402
Attn: Code 28

David W. Taylor Naval Ship
Research & Development Center
Annapolis, MD 21402
Attn: Code 2812

David W. Taylor Naval Ship
Research & Development Center
Annapolis, MD 21402
Attn: Code 2814

David W. Taylor Naval Ship
Research & Development Center
Bethesda, MD 20084
Attn: Code 1700

David W. Taylor Naval Ship
Research & Development Center
Bethesda, MD 20084
Attn: Code 1720

David W. Taylor Naval Ship
Research & Development Center
Bethesda, MD 20084
Attn: Code 1720.4

Naval Air Development Center
Warminster, PA 18974
Attn: Code 6043

Naval Air Development Center
Warminster, PA 18974
Attn: Code 6063

Naval Surface Weapons Center
White Oak, MD 20910
Attn: Code R30
Technical Library

Naval Surface Weapons Center
Dahlgren, VA 22448
Attn: Technical Library

Naval Civil Eng Library
Port Hueneme, CA 93043
Attn: Technical Library

Naval Underwater Systems Center
New London, CT 06320
Attn: Code 44
Technical Library

Naval Underwater Systems Center
Newport, RI 02841
Attn: Technical Library

Naval Weapons Center
China Lake, CA 93555
Attn: Technical Library

NRL/Underwater Sound Reference Det.
Orlando, FL 32856
Attn: Technical Library

Chief of Naval Operations
Department of the Navy
Washington, DC 20350
Attn: Code OP-098

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 05R25

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 05R26

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 09B31

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 55Y

Commander
Naval Sea Systems Command
Washington, DC 20362
Attn: Code 55Y2

Commander
Naval Air Systems Command
Washington, DC 20361
Attn: Code 03D

Commander
Naval Air Systems Command
Washington, DC 20361
Attn: Code 7226

Commander
Naval Air Systems Command
Washington, DC 20361
Attn: Code 310A

Commander
Naval Air Systems Command
Washington, DC 20361
Attn: Code 310B

US Naval Academy
Mechanical Engineering Dept.
Annapolis, MD 21402

Naval Postgraduate School
Monterey, CA 93940
Attn: Technical Library

Mr. Jerome Persh
Stf Specit for Matls & Struct
OUSDRE&E, The Pentagon
Room 3D1089
Washington, DC 20301

Professor J. Hutchinson
Harvard University
Div of Applied Sciences
Cambridge, MA 02138

Professor R.H. Gallagher
Worcester Polytechnical Institute
Worcester, MA 01609

Dr. Harold Liebowitz, Dean
School of Engr & Applied Sci
George Washington University
Washington, DC 20052

Professor G.T. Hahn
Vanderbilt University
Dept of Mech & Matrls Engr
Nashville, TN 37235

Professor Albert S. Kobayashi
Dept of Mechanical Engineering
University of Washington
Seattle, WA 98195

Professor L.B. Freund
Brown University
Division of Engineering
Providence, RI 02912

Professor B. Budiansky
Harvard Universtiy
Division of Applied Sciences
Cambridge, MA 02138

Professor S.N. Atluri
Georgia Institute of Technology
School of Engr & Mechanics
Atlanta, GA 30332

Professor J. Duffy
Brown University
Div of Engineering
Providence, RI 02912

Professor J.D. Achenbach
Northwestern University
Dept of Civil Engineering
Evanston, IL 60201

Professor F.A. McClintock
Dept of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Professor D.M. Parks
Dept of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. M.F. Kanninen
Southwest Research Institute
PO Drawer 28510
6220 Culebra Road
San Antonio, TX 78284

Professor F.P. Chiang
Dept of Mechanical Engr
State U of NY at Stony Brook
Stony Brook, New York 11794

Professor S.S. Wang
Dept of Theoretical & Applied Mechs
University of Illinois
Urbana, Illinois 61801

Professor Y. Weitsman
Civil Engr Department
Texas A&M University
College Station, Texas 77843

Professor I.M. Daniel
Dept of Mechanical Engr
Illinois Institute of Technology
Chicago, Illinois 60616

Professor C.T. Sun
School of Aeronautics & Astronautics
Purdue University
W. Lafayette, IN 47907

Professor J. Awerbuch
Dept of Mech Engr & Mechanics
Drexel University
Philadelphia, PA 19104

Professor T.H. Lin
University of California
Civil Engineering Dept
Los Angeles, California 90024

Professor G.J. Dvorak
Dept of Civil Engr
Rensselaer Polytechnic Institute
Troy, New York 12180

Dr. R.M. Christensen
Chemistry & Matrl Sci Dept
Lawrence Livermore National Laboratory
PO Box 808
Livermore, CA 94550

Professor J.R. Rice
Division of Applied Sciences
Harvard University
Cambridge, MA 02138

Professor W.N. Sharpe
The Johns Hopkins University
Dept of Mechanics
Baltimore, MD 21218

Professor C.F. Shih
Brown University
Division of Engineering
Providence, RI 02912

Professor A. Rosakis
California Institute of Tech
Graduate Aeronautical Laboratories
Pasadena, CA 91125

Professor D. Post
VA Polytechnic & State U
Dept of Engr Science & Mechanics
Blacksburg, VA 24061

Professor W. Sachse
Cornell University
Dept of Theoretical
& Applied Mechanics
Ithaca, NY 14853

Professor G.S. Springer
Stanford University
Dept of Aeronautics & Astronautics
Stanford, CA 94305

Professor H.T. Hahn
Washington University
Center for Composites Research
St. Louis, MO 63130

Professor S.K. Datta
University of Colorado
Dept of Mechanical Engineering
Boulder, CO 80309

Dr. M.L. Williams
School of Engineering
University of Pittsburgh
Pittsburgh, PA 15261

Dr. R.H. Gallagher
VP & Dean of Faculty
Worchester Polytechnic Institute
Worchester, MA 01609

Dr. D.C. Drucker
Dept of Aerospace Eng & Mechanics
University of Florida
Tallahassee, FL 32611

Dean B.A. Boley
Dept of Civil Engineering
Northwestern University
Evanston, IL 60201

master list - ldk107
July 24, 1986

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Date Entered)*

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER UWA/DME/TR-88/59	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* J-INTEGRAL MEASUREMENT USING MOIRÉ INTERFEROMETRY		5. TYPE OF REPORT & PERIOD COVERED Technical Report 6. PERFORMING ORG. REPORT NUMBER UWA/DME/TR-88/59
7. AUTHOR*(S)* M. S. DADKHAH, A. S. KOBAYASHI, F. X. WANG AND D. L. GRAESSER		8. CONTRACT OR GRANT NUMBER*(S)* N00014-85-K-0187
9. PERFORMING ORGANIZATION NAME ADDRESS Department of Mechanical Engineering, FU-10 University of Washington Seattle, Washington 98195		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of the Chief of Naval Research Arlington, VA 22217-5000		12. REPORT DATE April 1988 13. NUMBER OF PAGES 16
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Unlimited

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

J-integral, Biaxial Loading Machine, Moiré Interferometry, Elastic-Plastic Fracture Mechanics, Simultaneous Displacement Fields, Automated Data Reduction Displacement Fields, J-resistance Curve and Stable Crack Growth.

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An improved moiré interferometry, which records both the vertical and horizontal displacements simultaneously, was used to determine the J-integral within the confine of a constitutive relation. J-values, which are associated with stable crackgrowth in biaxially loaded 2024-T3 aluminum, single edge notched specimens, were found to be path independent and increased with crack extension.

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE *(When Date Entered)*

END
DATE
FILMED
7-88
DTIC